Mine Burial Experiments in the North Sea: Environmental Controls

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LONG-TERM GOALS

Our long term goal is to improve mine burial prediction capability by development and verification of physics-based mine burial models, including burial at impact and subsequent burial by scour and liquefaction and sand ridge migration.

OBJECTIVES

Our objectives are to collect environmental data with remote and in situ techniques, primarily seafloor properties, required to test operational and research-grade mine burial models during a NATO-sponsored experiment in the North Sea.

APPROACH

A "Mine Burial Specialist Team" (MBST) was established to formulate a united approach to improving mine burial prediction. The MBST primary objective is to develop a statistical model for prediction of mine burial and to model the resultant effect of burial on the performance on minehunting sonar. The initial field trail for the MBST "Critical Sea Test" was conducted off the Netherlands in the North Sea in November-December 1997. Our approach was to make detailed measurements of sediment physical and acoustic properties on sediments collected from two sites in the North Sea aboard the WFS PLANET during the MBST Critical Sea Test. Mine burial during the North Sea experiments was expected to result from scour, sand ridge migration, and/or liquefaction. Recent calculations presented to the MBST suggest burial by scour will dominate and liquefaction and sand ridge migration will occur only in water depths shallower than 10 meters (Mory, 1997).

During the experiments NRL measured the physical (geotechnical and geoacoustic) properties of the seafloor required to understand and model the mine burial processes. Other investigators are expected to measure the mine characteristics, movement, and burial as well as meteorological and oceanographic conditions. The sea floor was sampled with box cores, from which cylindrical subcores were collected. Bottom photographs were collected with 70-mm stereo cameras deployed remotely from the research vessel. Data on sediment roughness, compressional wave velocity and attenuation, porosity, density, permeability and grain size distribution from the experiment site were processed and parameterized for use with several burial models. The In Situ Sediment geoAcoustic Measurement

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system (ISSAMS) was used to measure sediment geoacoustic and physical properties in the upper 50 cm of the seafloor (Barbegelata et al., 1991; Richardson et al., 1995: Griffin et al., 1996). Geoacoustic and geotechnical probes are mounted on a large rigid frame and inserted into the sediment hydraulically. Operations are monitored by television camera mounted on the platform. Compressional and shear wave speed and attenuation were measured using a 4-probe pulse technique (Richardson, 1997). Sediment shear strength was measured using a direct drive cone penetrometer. Electrical resistivity was measured using a cylindrical probe with a circular array of elements. Pore pressure fluctuations were measured with a stand-alone piezometer. Measurement resolution is typically 1-5 cm in the vertical depending on which sediment property is measured.

WORK COMPLETED

We measured sediment physical and geoacoustic properties from sites C1 and B2 aboard the research vessel WFS PLANET. An extensive environmental data set was collected (Table 1). Although all sediment core and in situ geoacoustic data are processed at this time, piezometer and Acoustic Sediment Classification System (ASCS} data are not fully processed.

Table 1. Summary of data collected at Sites C1 and B2

MEASUREMENT	SITE C1 # of Samples/Sites	SITE B2 # of Samples/Sites
Gas Content	3	0
ISSAMS	6	1
ASCS profiles	13	6
Stereo Photography	21	66
Piezometer	1	0
Box Cores	5	7

Core, photogrammetry and data analysis have been completed. We have measured sediment sound speed and attenuation in diver cores as well as in situ. In situ shear wave speed and attenuation also have been measured and the data processed. Measurements of porosity, density, permeability, and grain size distribution have been completed on sediment cores. The measured sediment properties as determined from in situ and core samples were used to statistically estimate the model parameters required to predict mine burial by scour, liquefaction, and sand ridge migration.

RESULTS

The two sites investigated were a uniform fine sand at site C1 and a fine to medium sand with coarse shell lags on the western flanks of large sand ridges at site B2. The water depth at site C1 (13-16 m) suggested that liquefaction by wind waves would play a role in mine burial. The B2 site was deeper (20-30 m) and was subjected to strong tidal currents as well as wind-wave currents.

A complete characterization of site C1 is given in Table 2. The table includes measurements of the bottom water, laboratory measurements from sediment cores, in-situ measurements at depth within the C1 area, and calculated measurements based on acquired data. This summary provides values of virtually all water column and sediment properties needed to predict mine burial by the various MBST mine burial models. Table 3 depicts the average and range of values for geoacoustic properties measured at site B2.

Table 2. Sediment Characteristics at Site C1

Property	Mean	Range
Bottom Water		
Bottom Depth (m)	16	
Bottom Water Sound Speed (m s^{-1})	1481	
Bottom Temperature (°C)	8.5	
Bottom Salinity (ppt.)	31.6	
Density (kg m^{-3})	1025	
Gas Content (%)		0 - 0.02
Laboratory Measurements		
Mean Grain Size (ϕ)	2.07	2.00-2.16
Porosity (%)	35.9	33.0-38.8
Bulk Density (kg m^{3})	2073	2030-2120
Void Ratio	0.56	0.49-0.63
Grain Density (kg m^{-3})	2656	2652-2659
Compressional Wave Speed (m s^{-1})	1723	1707-1770
Compressional Wave Ratio	1.162	1.151-1.193
Compressional Wave Attenuation (dB m^{-1} @ 400 kHz)	94	58-196
Compressional Wave Attenuation (dB m^{-1} kHz^{-1})	0.23	0.15-0.49
Permeability (10^{-4} m sec-1)	1.68	1.04-2.23
In Situ Measurements		
Compressional Wave Speed (m s^{-1})	1689	1644-1715
Compressional Wave Ratio	1.140	1.115-1.166
Compressional Wave Attenuation (dB m^{-1} @ 38 kHz)	20	5-38
Compressional Wave Attenuation (dB m^{-1} kHz^{-1})	0.53	0.13-1.10
Shear Wave Speed (m s^{-1})	108	59-143
Shear Wave Attenuation (dB m^{-1} @ 1.0 kHz)	36	15-56
Roughness amplitude (10^{-2} m)	2.49	1.79-3.62
RMS Roughness (10^{-2} m)	0.655	0.449-0.993
Calculated Values		
Shear Modulus (real part) (10^{4} kPa)	2.41	0.72-4.23
Shear Modulus (imaginary part) (10^{4} kPa)	0.34	0.02-0.85
Sediment Bulk Modulus (10^{6} kPa)		5.89-6.59
Water Bulk Modulus (10^{6} kPa) no gas	2.14	
Water Bulk Modulus (10^{6} kPa) 0.02 % gas	1.6	

Table 3. Summary of values of sediment geoacoustic properties for experimental site B2. Shear wave measurements were made at 0.7 kHz and compressional wave measurements were made at 30 kHz.

Geoacoustic property	Mean	Range	Measurements
Compressional wave speed (m s^{-1})	1695	1673-1709	12
Compressional wave attenuation (dB m^{-1})	17	9.3-25.7	12
Shear wave speed (m s^{-1})	81	66.9-105.3	11
Shear wave attenuation (dB m^{-1})	45	34.4-50.6	3

The MBST has chosen the model of wave-induced momentary liquefaction proposed by Sakai to predict liquefaction potential in sandy sediments. Given the values of model input parameters presented in Table 2, the Sakai model requires a wave height nearly twice the 16-m water depth at site C1 for the sediments to liquefy. Liquefaction occurs when the excess pore pressure excesses the vertical stress due to the weight of the sand. If the pore fluid contains 0.02% gas, the lower compressibility only reduces the required wave height by 15 %. Both calculations are based on the conservative shallow-water wave case. Sensitivity studies of the Sakai model suggest that liquefaction potential is most sensitive to gas content (effective bulk modulus of the pore fluid), permeability and the shear modulus of the skeletal frame (shear wave speed). Liquefaction may also be induced by progressive buildup of pore pressure resulting from the hydrostatic fluctuations due to waves. This cyclic liquefaction may occur at much lower wave heights but is still unlikely to have occurred during the measurement period. In addition, the mine will bury when the static loading due to the weight of the mine itself exceeds the load bearing capacity of the seafloor. This will occur prior to sediment liquefaction. Laboratory experiments followed by field studies are required to evaluate the long-term effects of cyclic loading on the build up of excess pore pressure and the subsequent burial of mines.

Scour is predicted with the DRAMBUIE model using the inputs of 0.238 mm mean grain size, 1026 kg m^{-3} water density, 16 m water depth, 0.5 m cylindrical mine diameter, and 1220 kg m^{-3} mine density while varying the tidal currents yields the mine burial estimates. For this water depth, scour increases from 0.1 m at a current speed of 0.5 m s^{-1} to a maximum of 0.6 m when tidal currents exceed 1.5 m s^{-1}. These estimates need to be compared to the actual values determined by the registration mines implanted in the same area and to measured values of bottom current speed.

WISSP, the wave induced scour prediction program, indicates that when waves exceed 1.6 m height, mine burial on the order of 61% is predicted. For the indicated 16-m water depth, bedload transport (for a 0.238 mm grain size) begins when particle flow velocity exceeds 0.15 m s^{-1}. Suspended transport begins when particle flow velocity exceeds 0.8 m s^{-1}. For the highest wave height tested (4 m), the maximum particle flow velocity is 0.7 m s^{-1}, a velocity adequate to initiate bedload transport but not sufficient for suspended transport for this water depth.

Note that burial in excess of predicted values is certainly possible. None of the models tested allow interactions between the various mine burial processes. Such complex interactions can certainly contribute to burial greater that that predicted.

IMPACT/APPLICATION

The mine burial experiment results indicate that all pertinent parameters for predicting burial can be measured in a concerted effort with the tools available to validate existing burial models. For the environmental conditions encountered during the experiment, little if any burial is predicted to occur due to liquefaction or scour. At the B2 site insufficient time was allowed for sand ridge migration to present much burial of mines, despite the strong wave and tidal current regime. More experiments like this are necessary, although with a longer duration and more frequent monitoring of mine burial in order to understand how mines bury in sands and identify potential modeling improvements.

In addition to the parameters required for mine burial prediction, this experiment yielded a complete set of parameters necessary for the prediction of high-frequency backscatter. From the measurements of seafloor roughness and sediment geoacoustic properties, we were able to make predictions with the APL-UW composite roughness model for the uniform site C1 and over the areal extent of site B2. The result of these predictions is the first areal map of predicted backscatter strength based on real data.

TRANSITIONS

Upon completion of analysis our piezometer data will be utilized to interpret the liquefaction potential of the uniform fine sand site. These data will be helpful in interpreting the piezometer data collected in the NRL 6.2 Mine Burial Processes project in FY99 (Mike Richardson and Dan Lott), where we will use the NRL instrumented mine analogue in experiments at Duck, NC to monitor burial by scour, liquefaction, and sand ridge migration. With the complete analysis of in situ and core geoacoustic data, predictions from a high-frequency scattering model can be made for site B2. These predictions then can be used by the minehunting community to help discriminate the targets (mines) from the background reverberation (sea floor).

RELATED PROJECTS

1 –Using an Instrumented Mine to Validate Models Predicting Mine Burial, a project funded by ONR’s Ocean Measurement program begins in FY99.

2 – Results from modeling the mine burial constitute a valuable database for the NRL 6.2 Mine Burial Processes project (Mike Richardson and Dan Lott, principal investigators).

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